

## TWO YEARS ONBOARD THE MER OPPORTUNITY ROVER

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### ABSTRACT

The Autonomous Exploration for Gathering Increased Science (AEGIS) system provides automated data collection for planetary rovers. AEGIS is currently being used onboard the Mars Exploration Rover (MER) mission's Opportunity to provide autonomous targeting of the MER Panoramic camera. Prior to AEGIS, targeted data was collected in a manual fashion where targets were manually identified in images transmitted to Earth and the rover had to remain in the same location for one to several communication cycles. AEGIS enables targeted data to be rapidly acquired with no delays for ground communication. Targets are selected by AEGIS through the use of onboard data analysis techniques that are guided by scientist-specified objectives. This paper provides an overview of how AEGIS has been used on the Opportunity rover, focusing on usage that occurred during a 21 kilometer historic trek to the Mars Endeavour crater.

### 1. INTRODUCTION

The Autonomous Exploration for Gathering Increased Science (AEGIS) system provides automated data collection for planetary rovers. The AEGIS software was uploaded to the Mars Exploration Rover (MER) mission Opportunity rover in December 2009 to provide intelligent targeting capabilities for remote sensing instruments. AEGIS enables targeted data to be rapidly acquired with no required ground communication and at times otherwise not possible with traditional methods, such as during or immediately after long drives. Geological targets for rover remote-sensing instruments, especially narrow field-of-view instruments (such as the MER Mini-TES spectrometer and the 2011 Mars Science Laboratory (MSL) Mission ChemCam Spectrometer), are typically selected manually based on imagery that has already been transmitted back to the operations team on Earth. AEGIS enables the rover flight software to analyze imagery onboard through the use of data analysis techniques. This system allows the rover to autonomously select high priority science targets (typically rocks) based on criteria provided by scientists (e.g., rock size, shape, reflectance). When high priority targets are found, AEGIS can automatically acquire high quality data on those targets without requiring communication with the ground operations team. AEGIS is currently being used on the

Opportunity rover to automatically acquire 13 filter color images of interesting rock targets using the MER Panoramic cameras. AEGIS was also awarded the 2011 NASA Software of the Year Award based on its infusion and usage on the MER Mission

This paper will provide a brief overview of the AEGIS automated targeting capability and describe how it has been used during Opportunity's several year journey to the Mars Endeavour crater. In August 2008, the MER Opportunity rover began a long distance trek to Endeavour crater, which is a large impact crater located in the Mars Meridiana Planum. Endeavour is 22 kilometers (or 14 miles) in diameter and is the largest crater investigated by the Opportunity rover. At Endeavour, scientists expect to see much older rocks and terrain than in past areas on Mars and hope to find minerals that point to past signs of water and warmer conditions on Mars. After driving 21 kilometers from its position in August 2008 (and 33 kilometers from its original landing site), Opportunity successfully reached Endeavour crater in August 2011.

Opportunity performed many long drives on the way to Endeavour during which AEGIS was used to successfully detect and capture a number of different rock types including outcrop, crater ejecta, boulders and small cobbles. A number of example results are highlighted in this paper. Last, we discuss the next steps for AEGIS including current work in preparing AEGIS for eventual upload to the 2011 MSL Rover Mission, which is already in flight and scheduled to land in August 2012.

### 2. AEGIS SYSTEM OVERVIEW

The AEGIS system enables autonomous operation of science instruments that target specific terrain features, especially rocks with certain properties. A number of rover remote sensing instruments have a very narrow field-of-view and thus require selection of specific focused targets for data collection. Selecting targets for these instruments has traditionally been a lengthy process. Typically scientists would manually identify the interesting targets in context images that have already been downloaded on a previous sol. These context images are collected with wide field-of-view (FOV) cameras such as the MER navigation cameras, which have a 45 degree FOV. After reaching the end of

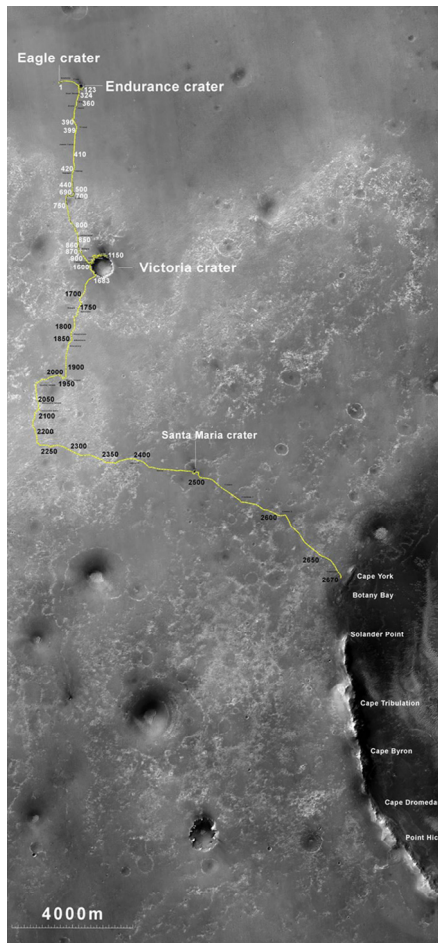


Figure 1. MER Opportunity rover traverse map showing Opportunity's path from landing to its current location at Endeavour crater. In September of 2008, the Opportunity rover left Victoria Crater to begin a long journey to Endeavour crater. In August 2011, Opportunity arrived at the rim of Endeavour after driving 21 kilometers from Victoria crater and a total of 33 kilometers for the entire mission.

a traverse, the rover performs only untargeted data collection until the context images can be downlinked, analyzed, and new measurement commands uplinked. At best this will happen on the next sol and it may require the rover to remain at the same location for several sols. Further it may never happen if it is decided the rover should immediately proceed to a new location due to other goals or engineering constraints.

AEGIS was designed to provide additional targeted data for the mission scientists. By analyzing image data onboard, AEGIS can autonomously select targets for onboard instruments and execute a set of measurement

activities. The capabilities of AEGIS are presently being used on the MER Opportunity rover by taking additional measurements with the Panoramic camera in a high-quality (multiple color filter) mode.

AEGIS is run as part of the MER onboard flight software, which imposes strict computational and resource constraints. All AEGIS components run onboard the MER 20 MHz RAD6000 flight processor, which has an early PowerPC instruction set, with 128 MB of RAM and 256 MB flash memory. Even though it processes full-frame images of over 1 MB each, AEGIS was required to run using less than 4 MB of total RAM to ensure other onboard processes were not impacted. Time efficiency was another important limitation since operations requiring a fraction of a second on a modern commercial processor could easily take tens of minutes on the MER flight processor. The AEGIS target selection process typically runs in less than 15 minutes on the MER processor. (On a quad-core 3.0 GHz Intel Core 2 with 8 GB of memory, AEGIS requires less than 1 second to process a typical image.)

The AEGIS technology focuses on the task of using onboard data analysis to acquire new instrument data on science targets, typically rocks, which have been identified in an opportunistic fashion. AEGIS performs seven major steps to autonomously acquire new targeted data on an interesting science target. These steps are shown in Figure 2 and described below:

- **Acquire an image with the MER navigation camera:** Scientists and other sequence team members select image parameters, such as the pointing direction and resolution, during the AEGIS sequencing process. The navigation camera is typically pointed at a terrain area where potential science targets may be in view.
- **Analyze the navigation camera image for potential terrain targets:** Targets for AEGIS typically correspond to rocks. AEGIS uses an algorithm called ROCKSTER to look for enclosed boundary contours (defined by intensity edges) in grayscale imagery.
- **Extract relevant target features:** AEGIS calculates a set of target features (or properties) for each candidate rock. These properties include measures of size, reflectance, shape, and rock location.
- **Prioritize targets and select top target:** This component uses a prioritization algorithm to analyze rock property data and determine a top candidate. Scientists provide a "target rock signature" in the command sequence. This signature specifies what property values are of interest in the local terrain. Example signatures are "high reflectance", "round shape", "large rocks with high eccentricity",

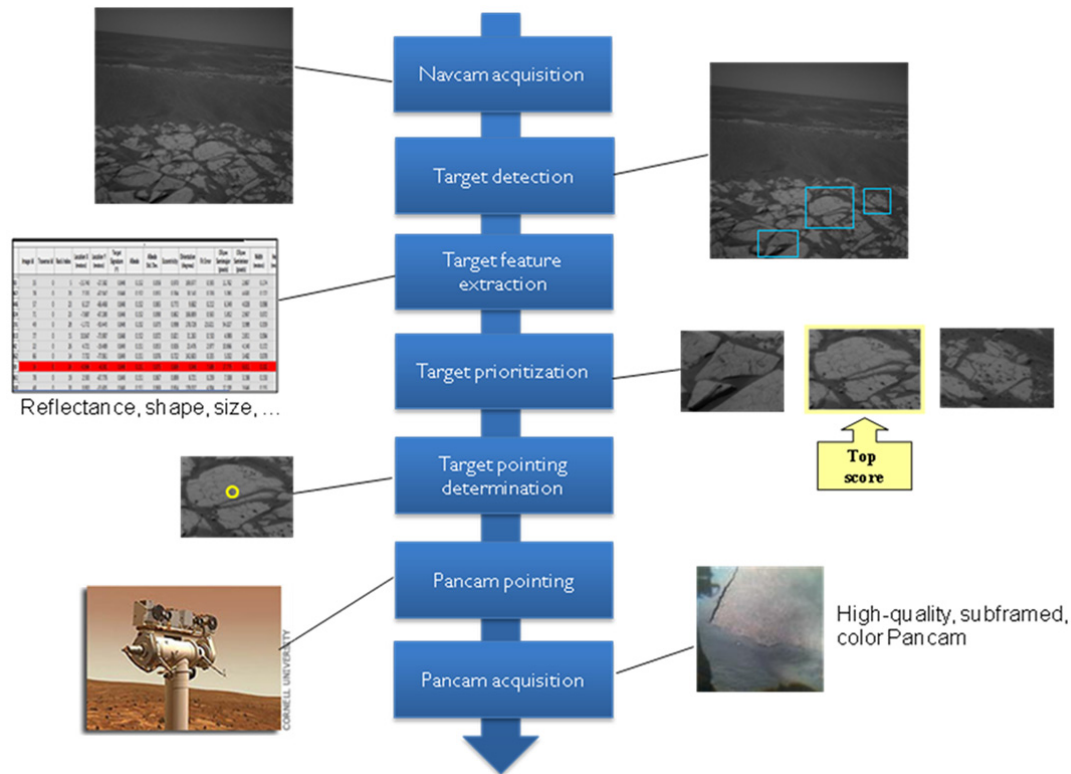


Figure 2. AEGIS Process Steps. When AEGIS is sequenced, the above series of steps is executed onboard the MER Opportunity rover. Parameters can be set during sequencing to specify navigation camera pointing, the “target rock signature” (e.g., rocks of large size and high reflectance/albedo), and settings for the panoramic camera (e.g., what filter set to use).

etc.

- **Determine 3D target pointing requirements:** After identifying the best scoring candidate rock, AEGIS selects a center point on the target using an inscribed circle method.
- **Point remote sensing instrument:** AEGIS points the panoramic cameras at the new target using the resulting center point.
- **Acquire new data:** AEGIS acquires additional data with the panoramic cameras. The ground sequencing team can pre-select the exact filters and other imaging parameters to use for each individual run. Typical command sequences take a quarter-framed (four degree FOV), multiple filter image with both left and right cameras. The rover downlinks these opportunistic images with other standard data products.

More details on how these steps are implemented in AEGIS and how AEGIS was integrated with the MER flight software can be found in [2].

### 3. AEGIS RESULTS ON THE WAY TO ENDEAVOUR CRATER

AEGIS was uploaded to the MER Opportunity rover in December 2009. After a series of checkout steps, AEGIS was deemed fully operational by March 2010. At this time, Opportunity had completed about one third of the distance needed to reach Endeavour. Thus many long drives were still being performed to reach Endeavour in a reasonable time period. Over the next 18 months, AEGIS was used approximately twenty times to autonomously detect and acquire data on interesting rock targets. Figure 3 highlights the various locations along the drive to Endeavour where AEGIS was used to select and acquire data on new targets. These runs were typically done at the end of long drives that covered anywhere between 50 to 150 meters per sol. During these runs AEGIS was used to successfully detect and capture a number of different rock types including outcrop, crater ejecta, boulders and small cobbles. Examples of collected target data from these runs are shown in Figures 4. A number of different “target rock signatures” were used to identify targets.

Properties that were often used to prioritize targets focused on rock size and rock reflectance (which could very successfully be used to distinguish lighter colored outcrop from darker loose rock, such as cobbles and crater ejecta). On several runs, only soil was visible in the image and AEGIS correctly returned a result of no targets found. False positives have also occurred. For instance, in one run, AEGIS was allowed to consider

very small targets (less than 25 pixels), and found a set of very small false positive targets in the sand (though no rocks were in the scene). AEGIS parameters have since been modified to prevent similar occurrences.

All target data was acquired by AEGIS used the MER Panoramic cameras which can acquire high-resolution image data using up to 13 color filters. For these runs

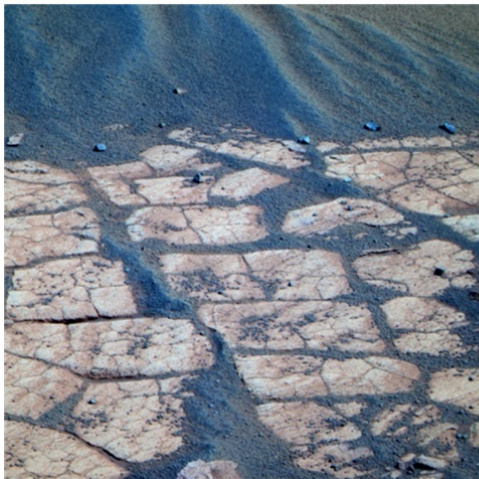


Figure 4. Examples of targeted data collected during AEGIS runs. AEGIS has been used in a variety of terrains to collect data on rock classes such as outcrop, crater ejecta and boulders. This data was collected using the MER Panoramic cameras which can collect high quality image data using 13 color filters. All of this data was collected autonomously by the AEGIS software during or after an Opportunity rover drive.

the Panoramic camera was run either in a full-frame mode (which covers a 16 degree FOV) and a quarter-frame mode (which covers a 4 degree FOV). The quarter-frame mode highlights how AEGIS can be used to accurately point at targets even if the pointing instrument only covers a very small area of terrain.

#### 4. AEGIS PLANNED USAGE ON THE MSL MISSION

We are currently applying AEGIS for automated targeting on the Mars Science Laboratory (MSL) Rover mission, which launched in November 2011 and lands the Curiosity rover on the surface of Mars in August 2012. AEGIS will be used to collect targeted data using the MSL ChemCam spectrometer [4], which is

illustrated in Figure 5. ChemCam is a Laser Induced Breakdown Spectrometer (LIBS), which can identify elemental composition information on rocks and soil. ChemCam operates by vaporizing a small portion of rock and then collecting the light spectrum that is emitted. ChemCam can sample rocks from a distance between 1 to 7 meters from the rover and will be used to both survey rocks and identify rocks appropriate for more detailed sample analysis. We are currently working with the MSL ChemCam team to enable AEGIS to be uploaded to Curiosity and enable automated targeting with the ChemCam instrument. Similar to MER, AEGIS will analyze wide-angle Navigation camera images in order to determine high priority science targets that warrant ChemCam analysis. AEGIS will be used to collect single ChemCam

measurements on individual rock spots as well as measurement rasters where, for example, a 1x3 or 1x5 raster of measurements is collected on a small rock area. The AEGIS software will examine similar properties as detected on the MER mission, including size, reflectance and shape. We are also evaluating the use additional rock properties that could be used in prioritizing targets on MSL or on future rover missions. For instance, one extension could be to incorporate the evaluation of new target features, such as texture, layering, or color. Use of these features has and currently is being explored in other work [1,3].

## 5. CONCLUSIONS

In summary, AEGIS enables autonomous recognition of scientifically interesting targets in MER rover navigation camera imagery. These targets can then be successfully characterized without requiring a communication cycle with mission operations on Earth. New measurements with the MER Panoramic cameras can be acquired during or immediately after a long drive, and before images of the rover's current location have been acquired and analyzed by human operators. AEGIS was uploaded to the MER Opportunity rover in December 2009. The system has been successfully run a number of times on the surface of Mars and has consistently picked out appropriate targets. The MER mission plans to continue the use of AEGIS to enable automated targeting for the MER panoramic camera. Future runs should provide additional data that can be used to further evaluate AEGIS' performance. AEGIS is also planned for usage on the 2011 MSL Rover Mission and will collect targeted at with the MSL ChemCam spectrometer.

## 6. ACKNOWLEDGEMENTS

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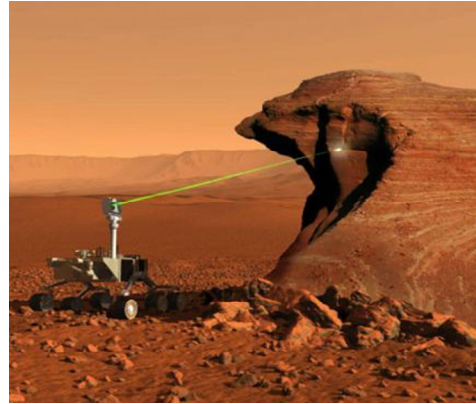


Figure 5. Artist's illustration of the Mars Science Laboratory (MSL) Rover ChemCam Spectrometer. ChemCam is a Laser Induced Breakdown Spectrometer that can identify elemental composition information on rocks and soil. Currently, AEGIS is planned for use on MSL to enable automated targeting of the ChemCam instrument.

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